



Search for a Dijet Resonance in Events with Jets and Missing Transverse Energy in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We report a search for a resonance with mass of $145 \text{ GeV}/c^2$ in events with only two or three jets and large missing transverse energy. This search is sensitive to the production of such a resonance in association with a W or Z boson, where the boson decays leptonically with one or more neutrinos in the final state. We use the full data set collected by the CDF II detector at the Tevatron collider at a proton-antiproton center-of-mass energy of $\sqrt{s} = 1.96$ TeV. This data corresponds to an integrated luminosity of 9.1 fb^{-1} . We perform a study of the invariant mass distribution of jet pairs in this final state. We find good agreement of the data and the standard model prediction, and thus set 95% credibility level upper limits for the dijet resonance of $145 \text{ GeV}/c^2$ with different production scenarios.

I. INTRODUCTION

A study of the dijet invariant mass (m_{jj}) distribution in events with jet pairs produced in association with a W boson was recently performed by the CDF collaboration with an integrated luminosity corresponding to 4.3 fb^{-1} [1]. In that analysis, the W boson decays leptonically to $\ell\nu$ ($\ell = e$ or μ), where an identified electron or muon is required in the event selection. Ref [1] reported evidence of an excess of events corresponding to 3.2 standard deviations (s.d.) with respect to the standard model (SM) hypothesis at $m_{jj} = 145 \pm 5 \text{ GeV}/c^2$. In that study, the excess was modeled assuming a Gaussian distribution, centered at $145 \text{ GeV}/c^2$ with an rms width of $14.3 \text{ GeV}/c^2$, which corresponds to the expected experimental m_{jj} resolution for the CDF detector. The acceptance and selection efficiencies for such a resonance was estimated by simulating the Higgs boson (H) in association with the W boson, where a Higgs boson mass of $150 \text{ GeV}/c^2$ is assumed. Assuming the excess is caused by a particle X with $Br(X \rightarrow jj) = 1$, the estimated production cross section of $\sigma(p\bar{p} \rightarrow WX) = 3.1 \pm 0.8 \text{ pb}$.

The D0 collaboration has performed a similar study [2] with the same amount of data collected with the D0 detector. However, it finds no evidence for such an excess at the expected mass. The D0 collaboration also has investigated the range of m_{jj} from 110 to $170 \text{ GeV}/c^2$, the data is found to be consistent with the standard model prediction.

Many theoretical models have been proposed to explain this excess. Among them, a Z' model and a technicolor model are relevant to the study in this letter [3, 4]. In these models, a hypothetical particle can be produced in association with either a W boson or a Z boson. In analogy with the low mass \cancel{E}_T +jets Higgs boson search performed at CDF [5], we thus search for WX and ZX production in the same final state. Here the electron or muon from W decay is not identified, but the hadronic decay of the τ from $W \rightarrow \tau\nu$ is reconstructed as a jet in the event.

In this letter we report a search for dijet resonance in the m_{jj} spectrum in the \cancel{E}_T +jets final state.

II. DATA SAMPLE AND EVENT PRESELECTION

The data are collected by CDF II [6], a general-purpose detector used to study the Tevatron $p\bar{p}$ collisions at a center-of-mass energy of 1.96 TeV. CDF II contains a tracking system consisting of a cylindrical open-cell drift chamber and silicon microstrip detectors immersed in a 1.4 T magnetic field parallel to the beam axis. Electromagnetic and hadronic calorimeters surrounding the tracking system measure particle energies. Drift chambers and muon scintillators located outside the calorimeter identify muons.

We consider events that trigger the data acquisition due to the presence of two calorimeter clusters and significant amount of \cancel{E}_T . We also consider events that satisfy the inclusive \cancel{E}_T trigger which requires \cancel{E}_T greater than 45 GeV. Jets are reconstructed using the JETCLU algorithm [7] with a clustering radius of 0.4 in azimuth-pseudorapidity space (ϕ, η) [8]. Jet energies are corrected [9] for nonuniformities of the calorimeter response as a function of η , energy contributed by multiple $p\bar{p}$ interactions in the event, and calorimeter nonlinear response.

In order to retain only the events for which the trigger system is fully efficient, we select events with $\cancel{E}_T > 50 \text{ GeV}$ and two or three energetic jets. We require the two leading jets to have E_T greater than 35 GeV and 25 GeV, respectively, with $|\eta(j_i)| < 2$ and one of them satisfying $|\eta(j_i)| < 0.9$. We require the separation of the jets to satisfy $\Delta R(j_1, j_2) > 1$. By considering events with a third jet with E_T greater than 15 GeV and $|\eta| < 2.4$, we thus accept signal events with an initial- or final-radiation jet, or those with a hadronically decaying τ in the final state. We reject events with identified electrons or muons with $p_T > 20 \text{ GeV}/c$.

III. BACKGROUND MODELING

We model the SM signal and background processes using a variety of Monte Carlo (MC) simulation programs. The diboson processes (WW , WZ and ZZ) are generated with PYTHIA [10]. The SM cross section for diboson are 12.4 pb for WW , 3.7 pb for WZ and 3.6 pb for ZZ . The top-quark pair production is generated with PYTHIA by assuming a top-quark mass of $172.5 \text{ GeV}/c^2$ [11]. Its contribution is normalized to the approximate next-to-next-to-leading order cross section [12]. The single top-quark productions, both s - and t -channel, are modeled using POWHEG [13] and normalized to NLO cross sections [14, 15]. The productions of W/Z plus jets are simulated by ALPGEN [16] with showering and hadronization performed by PYTHIA. The normalization of the W/Z plus jets will be discussed later.

We model the QCD multijet events, a major source of background in the final state of jets and \cancel{E}_T , with a data-driven method. The QCD multijet events have very large production rate at a hadron collider. Therefore a prohibitively large Monte Carlo sample would be needed to accurately describe this background. We define missing transverse momentum $\vec{\cancel{p}}_T$, a variable similar to $\vec{\cancel{E}}_T$, as the negative vector sum of the charged particles momenta by using the reconstructed information from the tracking system. As shown in Fig. 1, $\vec{\cancel{E}}_T$ and $\vec{\cancel{p}}_T$ are aligned in processes with a neutrino in

the final state, such as VV , but aligned or anti-aligned in the data, which is dominated by QCD contributions. For QCD multijet events, \vec{E}_T originates from jet energy mismeasurement and aligns to the subleading jet. However, as the amount of summed track momentum within the jet cone is somewhat random, either the leading or subleading jet (as ordered by E_T) can have greater amount of p_T . When considering the angular separation between the \vec{E}_T and \vec{p}_T in an event, QCD multijet events thus have peaks toward 0 and π . With such feature, one thus can suppress the QCD multijet background by rejecting data events where $\Delta\phi(\vec{E}_T, \vec{p}_T) > \pi/2$, and moreover, can use those rejected events to model the QCD multijet background in the accepted region ($\Delta\phi(\vec{E}_T, \vec{p}_T) < \pi/2$). More details can be found in [17], and examples of analyses that have used this technique in the past are given in Refs. [5, 18, 19].

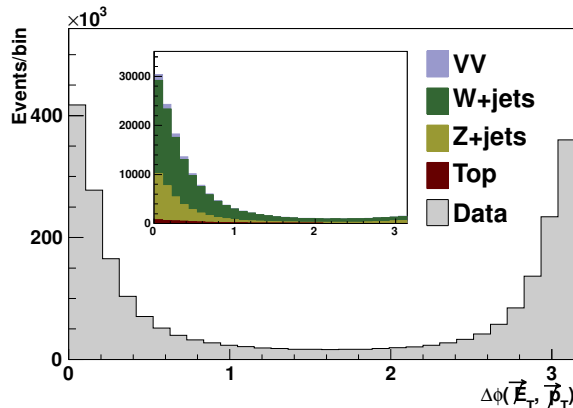


FIG. 1: The $\Delta\phi(\vec{E}_T, \vec{p}_T)$ distribution for events that satisfy the preselection requirements. Data, in which 94% are estimated to be QCD multijet, have \vec{E}_T and \vec{p}_T either aligned or anti-aligned, whereas productions with real neutrinos always have \vec{E}_T and \vec{p}_T aligned.

IV. SIGNAL REGION

The event selection described above yields over 2 million candidate events, in which 94% are estimated to be QCD multijet. To reduce the QCD multijet background, we require the azimuthal distance between the direction of \vec{E}_T and subleading jets, $\Delta\phi(\vec{E}_T, j_i)$ to be greater than 0.8. We also require $\cancel{p}_T > 20$ GeV and large \vec{E}_T significance ($\vec{E}_T / \sqrt{\sum E_T} > 3.5$ GeV^{1/2}, where $\sum E_T$ is the scalar sum of transverse energy deposited in the calorimeter), and $\vec{H}_T / \vec{E}_T < 1.2$, where \vec{H}_T is the magnitude of negative vector sum of jet transverse energies. These selections reduce the QCD multijet events by more than 99%.

The normalization of the W/Z plus jets and the QCD multijet events are determined by fitting the \vec{E}_T distribution, which provides discrimination between signal- and background-like processes. Figure 2 shows the distribution of the \vec{E}_T , in which the top and diboson production cross sections are fixed to their theoretical predictions and the W/Z plus jets and QCD multijet normalizations are determined from the fit. The distributions for 1st jet E_T , 2nd jet E_T and $\Delta\phi(j_1, j_2)$, variables highly correlated to the dijet invariant mass m_{jj} , are shown in Fig. 3. The measured yields for signal and backgrounds in the signal region are given in Table I.

V. SYSTEMATIC UNCERTAINTIES

We consider several systematic uncertainties affecting this analysis. The dominant systematic sources are the uncertainties on multijet normalization (19%) and the background cross sections (6.5 - 30%). We also consider uncertainties from the jet energy scale (JES) [9] (1.4 - 12.9%), the luminosity measurement [20] (5%), parton density functions (2%), lepton veto (2%) and trigger efficiency (0.4 - 1.5%). We also assign systematic uncertainties, based on the variation in the shape of the distribution of kinematic quantities. For Monte Carlo samples, we included $\pm 1\sigma$ variation of the jet energy scale as a shape uncertainty. We also vary the Q^2 scale, a parameter in the perturbative expansion used to calculate the matrix elements in the ALPGEN generator, to generate the shape uncertainty templates for the W/Z plus jet backgrounds. For QCD multijet events, we vary the amount of contamination from electroweak production in predicting the QCD shape as a shape uncertainty.

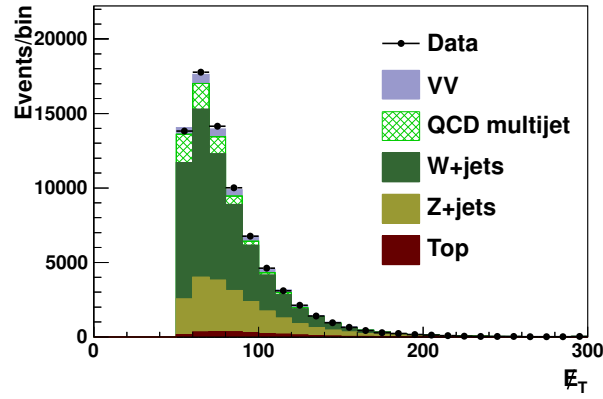


FIG. 2: The \cancel{E}_T distribution for events that satisfy the signal region definition. It is used to determine the normalization of the W/Z +jets and the QCD multijet backgrounds.

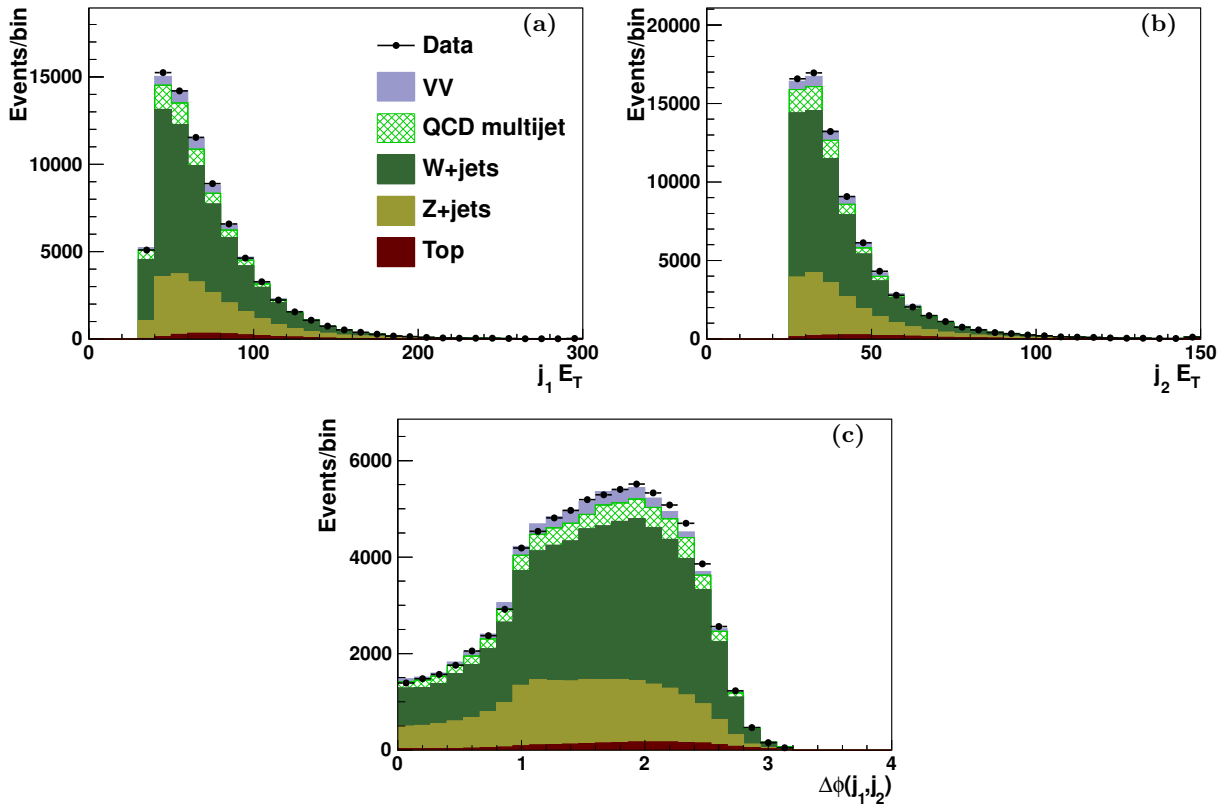


FIG. 3: Distributions for (a) 1st jet E_T , (b) 2nd jet E_T and (c) $\Delta\phi(j_1, j_2)$ in the signal region.

VI. RESULTS

A. Diboson Measurement

We use the invariant mass reconstructed from the two leading jets to measure the cross section of diboson production. Figure 4 shows the dijet invariant mass distribution as well as a comparison of the diboson signal with the background-subtracted data, which provides a strong consistency check on our background model. The cross section is calculated using a Bayesian maximum likelihood method [21] where a flat prior for the signal cross section is used in this analysis. We treat systematic uncertainties using a Bayesian marginal likelihood method. The cross section $\sigma(p\bar{p} \rightarrow VV)$ is

TABLE I: Number of expected signal and background events compared to data in the signal region. The errors include statistical and systematic uncertainties.

Process	Yield
WW	2058 ± 184
WZ	732 ± 66
ZZ	383 ± 34
Top	2197 ± 204
W +jets	45530 ± 13989
Z +jets	19765 ± 6073
QCD multijet	6155 ± 1170
Total expected	76820 ± 15302
Data	76861

measured to be $13.6^{+3.3}_{-3.2}$ pb.

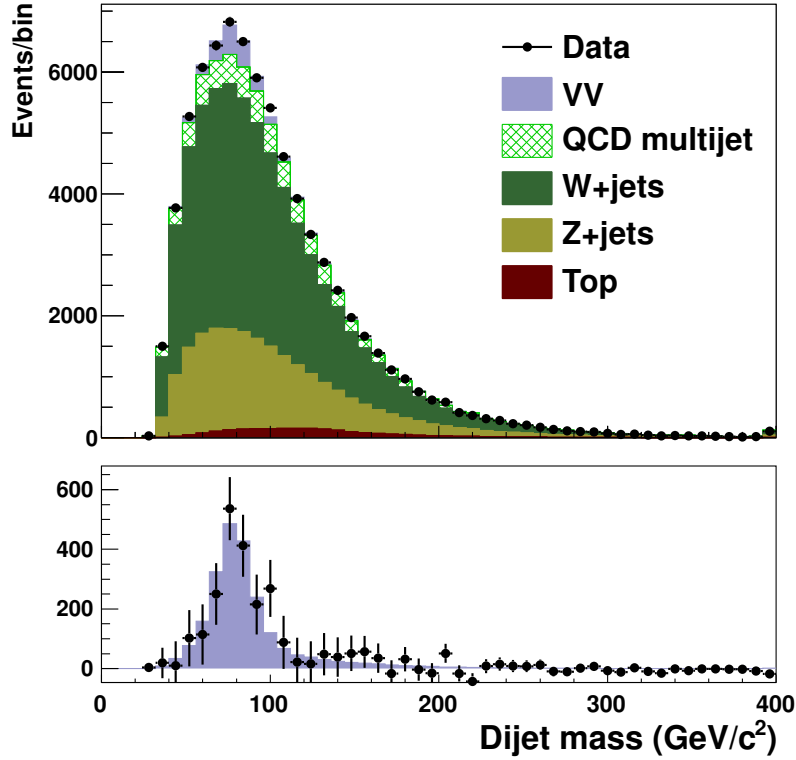


FIG. 4: The dijet mass distribution for events that satisfy the signal region definition. Top: Comparison between data and fitted signal and background. Bottom: Comparison of the fitted diboson signal (filled histogram) and the background-subtracted data (points).

B. Limit on Dijet Resonance

We use the simulation of the Higgs boson produced in association with the W or Z boson to estimate the signal acceptance, assuming a Higgs boson mass of $150 \text{ GeV}/c^2$. As the composition of WX and ZX productions varies by theoretical models, we set the upper limits with three scenarios: (1) $\sigma_{WX} = 3.1 \text{ pb}$ and no ZX , (2) $\sigma_{WX} = 3.1 \text{ pb}$ and $\sigma_{ZX} = 1 \text{ pb}$, (3) $\sigma_{WX} = 3.1 \text{ pb}$ and $\sigma_{ZX} = 2 \text{ pb}$. The upper limits are presented in Tab. II and Fig. 5.

Signal scenarios	Expected upper limits	Observed upper limits
$\sigma_{WX} = 3.1$ pb and no ZX	1.29 pb	2.73 pb
$\sigma_{WX} = 3.1$ pb and $\sigma_{ZX} = 1$ pb	1.01 pb	2.14 pb
$\sigma_{WX} = 3.1$ pb and $\sigma_{ZX} = 2$ pb	0.89 pb	1.89 pb

TABLE II: Expected and observed 95% C.L. upper limits on the three signal scenarios

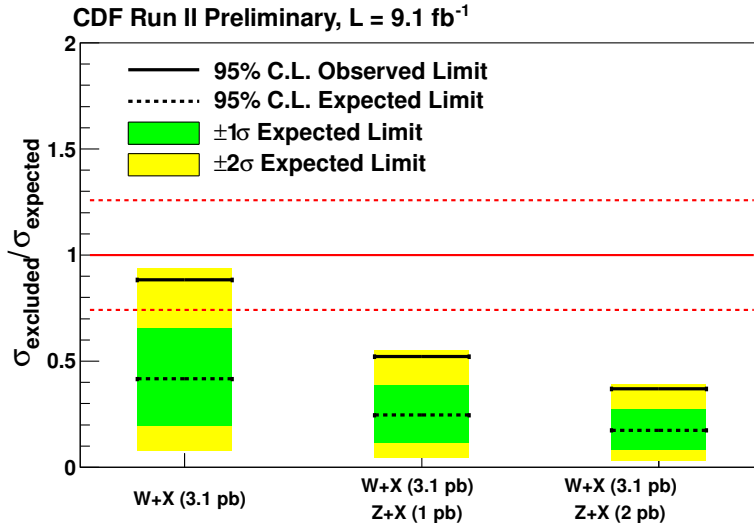


FIG. 5: Observed and expected (median, for the background-only hypothesis) 95% C.L. upper limits on three signal scenarios divided by the expected cross sections. The red lines are for the expected cross sections (solid) and their uncertainties (dash).

VII. CONCLUSION

In conclusion, we have measured the cross section of the diboson production in the events with energetic jets and large missing transverse energy using the full CDF data set that correspond to an integrated luminosity of 9.1 fb^{-1} . We measure a diboson cross section value of $\sigma(p\bar{p} \rightarrow VV) = 13.6^{+3.3}_{-3.2} \text{ pb}$, in good agreement with the standard model prediction. We set 95% CL upper limits for the dijet resonance produced in association with a W or Z bosons with different production scenarios.

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- [1] T. Aaltonen *et al.*, (CDF Collaboration), Phys. Rev. Lett. **106**, 171801 (2011).
 - [2] V.M. Abazov *et al.*, (D0 Collaboration), Phys. Rev. Lett. **107**, 011804 (2011).
 - [3] P. Fox, J. Liu, D. Tucher-Smith, N. Weiner, arXiv:1104.4127 (2011)
 - [4] E. Eichten, K. Lane, A. Martin, arXiv:1104.0976 (2011)

- [5] T. Aaltonen *et al.*, (CDF Collaboration), Phys.Rev.Lett. 104, 141801 (2010)
- [6] D. Acosta *et al.*, (CDF Collaboration), Phys. Rev. D **71**, 032001 (2005).
- [7] F. Abe, *et al.* (CDF collaboration), Phys Rev. D **45**, 001448 (1992).
- [8] CDF uses a cylindrical coordinate system with the z axis along the proton beam axis. Pseudorapidity is $\eta = -\ln(\tan(\theta/2))$, where θ is the polar angle relative to the proton beam direction, and ϕ is the azimuthal angle while $p_T = |p|\sin\theta$, $E_T = E\sin\theta$.
- [9] A. Bhatti *et al.*, Nucl. Instrum. Methods A **566**, 375 (2006).
- [10] T. Sjostrand, S. Mrenna, and P. Skands, J. High Energy Phys. 05, 026 (2006).
- [11] T. Aaltonen *et al.* [CDF and D0 Collaborations], Phys. Rev. D **86** (2012) 092003
- [12] U. Langenfeld, S. Moch, and P. Uwer, Phys. Rev. D **80**, 054009 (2009).
- [13] S. Alioli *et al.*, J. High Energy Phys. 06, 001 (2010).
- [14] B. W. Harris *et al.*, Phys. Rev. D **66**, 054024 (2002).
- [15] Z. Sullivan, Phys. Rev. D **70**, 114012 (2004).
- [16] M. L. Mangano, M. Moretti, F. Piccinini, R. Pittau and A. Polosa, J. High Energy Phys. 07, 001 (2003).
- [17] M. Bentivegna, D. Bortoletto, Q. Liu, F. Margaroli and K. Potamianos, arXiv:1205.4470 (2012).
- [18] T. Aaltonen *et al.*, (CDF Collaboration), Phys. Rev. D **81**, 072003 (2010).
- [19] T. Aaltonen *et al.*, (CDF Collaboration), Phys. Rev. Lett. **107**, 191803 (2011).
- [20] D. Acosta *et al.*, Nucl. Instrum. Methods A **494**, 57 (2002).
- [21] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. D **82**, 112005 (2010).